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New technique for researching the absorption signal fronts of laser radiation on blood vessels

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Abstract. The analysis of pulse oximetry as a method of rapid diagnosis of the state of the body in real time was performed. Data are presented that the high rate of pulse wave propagation through the arteries in patients with COVID-19 may indicate a high risk of death. It is noted that modern device designs and pulse wave signal processing methods have a number of disadvantages. This leads to an unreliable interpretation of the data. Using a charge-coupled device increases the accuracy of measuring the position of maxima and minima on the time scale. This makes it possible to determine the moment of closure of the aortic valves of the left ventricle more accurately. The registered pulse waves of various people are presented, as well as the results of the study of the time intervals of the rising and falling fronts.

Keywords: blood flow, pulse wave, laser radiation, absorption signal, oxygen, time, rise and fall front, measurement error

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Новая методика исследования фронтов пульсовой волны, регистрируемой на кровеносных сосудах

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Аннотация. Выполнен анализ пульсоксиметрии как метода экспресс-диагностики состояния организма в режиме реального времени. Представлены данные о том, что высокая скорость распространения по артериям пульсовой волны у пациентов с COVID-19 может свидетельствовать о высоком риске летального исхода. Отмечено, что современные конструкции приборов и методы обработки сигнала пульсовой волны обладают рядом недостатков. Это приводит к недостоверной интерпретации данных. Использование прибора с зарядовой связью увеличивает точность измерений положения максимумов и минимумов на временной шкале. Это позволяет более точно определить момент закрытия аортальных клапанов левого желудочка. Представлены зарегистрированные пульсовые волны различных людей, а также результаты исследования временных интервалов фронтов нарастания и спада.

Ключевые слова: кровоток, пульсовая волна, лазерное излучение, сигнал поглощения,

кислород, время, фронт нарастания и спада, погрешность измерения

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Introduction

In conditions of environmental degradation, acceleration of the rhythm of life and the level of stress load, people began to regularly monitor their health [1–6]. Express diagnostic methods in the modern world are very often used to solve various problems [6–9]. It is very important for a person to be able to perform this diagnosis independently. Therefore, pulse oximetry has become widespread among express diagnostics, in addition to measuring temperature and pressure [3, 4, 9–11]. Its advantages include noninvasiveness of measurements when obtaining pulse data and percentage of oxygen saturation of the blood.

In addition, studies by various scientists have shown that a number of patients with COVID-19 have a higher rate of pulse wave propagation through the arteries. Considering this factor, sources of laser radiation at various wavelengths for pulse oximeters are being developed for its registration [12, 13]. According to British and Italian researchers, the probability of death in COVID-19 can be considered increased if the pulse wave velocity does not exceed 13 meters per second. It should be noted that for most people of different ages (the norm in terms of velocity) is 5.5–8 meters per second [14, 15].

It should be noted that modern pulse oximeter designs and pulse wave signal processing methods have a number of disadvantages [16–21]. This leads to errors in measuring the pulse and the percentage of oxygen saturation of the blood (up to 50%), as well as distortion of the pulse wave shape. Therefore, the purpose of our work is to study the pulse wave fronts to obtain additional information about the state of human health. This is extremely relevant recently, especially in the context of a pandemic.

Features of pulse wave fronts formation and methods of their investigation

Numerous studies have shown that transmission pulse oximetry using a laser radiation absorption signal has the greatest advantages for personal use at various times (for example, with deterioration of health, heavy loads, etc.) [16–18]. The classical form of the laser radiation absorption signal (pulse wave) recorded using a photodetector is shown in Fig. 1.

The presented signal has two peaks (maxima) and three minima. The pulse value per minute is determined by the distance between the main maxima (corresponding to time t_2) in the pulse wave and their number. By registering two absorption signals of laser radiation with different wavelengths λ_1 = 662 nm and λ_2 = 907 nm, the percentage saturation of blood hemoglobin with oxygen is determined.

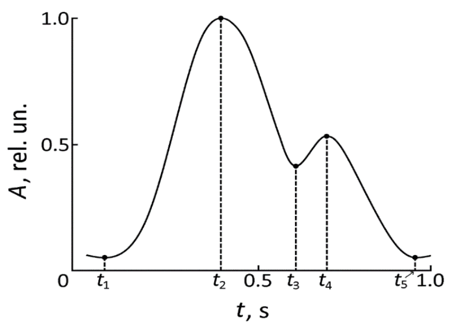

Fig. 1. Pulse wave shape detected by the photodetector from the laser radiation absorption signal

To obtain additional information about the state of human health, the values of the time intervals $\Delta t_1 = t_2 - t_1$, $\Delta t_2 = t_3 - t_2$, $\Delta t_3 = t_4 - t_3$ and $\Delta t_4 = t_5 - t_4$ are important. As well as the nature of the change in the fronts of the rise and fall of the pulse wave. These data may make it possible in the future to noninvasively determine the compliance of the cardiovascular system, as well as to evaluate (determine the order of magnitude) the value of the blood velocity in the veins and arteries. Data on the intervals Δt_1, Δt_2, Δt_3 and Δt_4 were used by a number of authors to construct mathematical models of rising and falling fronts [16, 18, 20–23].

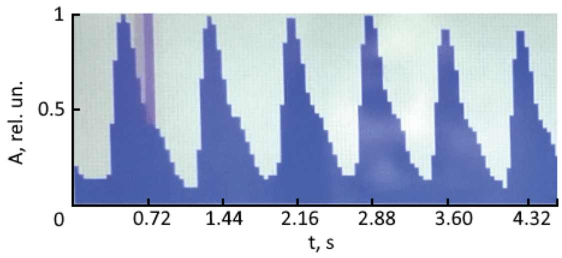

Fig. 2. Shape of the absorption signal of the recorded signal in transmission pulse oximetry
Data for female patient showing symptoms of COVID-19 for less than 2 weeks (age 22)

In a number of papers, the authors tried to obtain additional information about the state of human health using envelopes [21–26], for the mathematical description of which an exponential function of the form exp(-Kt) was used. This method turned out to be ineffective. Therefore, the most appropriate decision in this situation was to register the absorption signal of laser radiation using a CCD array. In this case, the pulse wave signal is recorded in the form of steps that correspond to the levels of cell filling with charge (quantization of the shape of the pulse wave fronts). Fig. 2 shows the recorded signal of laser radiation absorption using a CCD.

Our research has shown that for different people, the parameters of the steps (amplitude and their duration), as well as their number in the pulse wave, differ from each other. These differences are related to the pulsation of the walls of the blood vessel during the passage of blood flow during contraction of the heart muscle, the elasticity of blood vessels and veins, and may also be the composition of blood. The technique of recording absorption signals using CCD does not significantly affect the change in the parameters of the steps. Other factors influence, for example, when changing the position of a person's placement, the recorded pulse wave signal changed (the number and parameters of the steps changed).

When using the parameters of the steps to measure the characteristics of the pulse wave (time intervals Δt), the signal-to-noise ratio of the recorded absorption signal will be of great importance. As a result of various studies [18, 21, 22, 24, 25] of measuring the amplitude of the recorded laser radiation from the angle of incidence of the laser beam on the surface of the finger, the following was established. The value of the signal-to-noise ratio in the recorded absorption signal will be maximum if the direction of the angle of incidence of the laser radiation on the surface of the finger is perpendicular to the blood flow in the vessel. Therefore, choosing the appropriate sensor configuration, which is installed on the finger, allows you to get an increase in the signal–to-noise ratio by 5-10%, which in some cases can affect the accuracy of diagnostics with a weak absorption signal (very thin blood vessels). It should be noted that the wavelength λ has the greatest influence on the signal-to-noise ratio of the recorded absorption signal. In modern industrial devices, two laser radiation sources with $\lambda_1 = 662 \pm 2$ nm and $\lambda_2 = 940 \pm 2$ nm are used to register a pulse wave based on measurements of the amplitudes of the absorption signal. These wavelengths have been calculated for a long time for typical human data from the twentieth century.

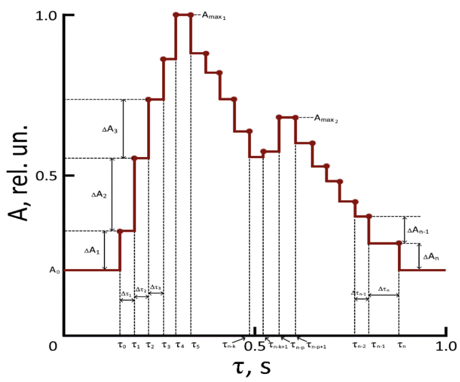

Fig. 3. Shape of the absorption signal recorded in transmission pulse oximetry

The results obtained showed that in most people, the maximum amplitude of the pulse wave is shifted to the region of smaller wavelengths of the red laser radiation range. Therefore, in order to increase the signal/noise of the recorded signal of absorption of reduced hemoglobin in these cases, it is necessary to use laser radiation with λ_1 less than 650 nm. Similar studies have been done to change λ_2. It was found that to increase the signal/noise of the detected absorption signal of

In case of using a CCD, will reduce the resolution of the device in the formation of steps in the pulse wave signal, part of the steps with a small amplitude will either not be formed or them combination with the neighboring one will occur, which will lead to measurement errors of the values of Δt_T. To increase the accuracy of measuring the time intervals of the pulse wave fronts $\mathbf{\Delta} t_1$, $\mathbf{\Delta} t_2$, $\mathbf{\Delta} t_3$ and $\mathbf{\Delta} t_4$, it is proposed to use the following technique. Fig. 4 shows the pulse wave signal formed in the form of steps. The timeline scale is defined as follows. The counter counts Nm correspond to the number of peaks per minute (amplitude maxima). Maxima (A_{max_2}) corresponding to the dicrotic rise (Fig. 3) are not considered.

Next, a time ruler is built with a scale of 60/*Nm* in seconds. The grid labels correspond to the maxima of the signal peaks. There is already an error in this approach, since the integer number of peaks does not fit into 60 s. Therefore, we propose to introduce a correction factor $\Delta T = 30/(N_m)^2$. In this case, the following formula should be used to determine the distance between the peaks of T:

$$T = \frac{60}{N_m} + \frac{30}{(N_m)^2}. \quad (1)$$

In the case of small values (less than 70 beats per minute), it is proposed to introduce additional coefficients in (1):

$$T = 60\left(\frac{1}{N_m} + \frac{2}{(N_m)^2} + \ldots + \frac{n}{(N_m)^n}\right), \quad (2)$$

where n can vary from 3 to 10 or more.

With an increase in n, the accuracy of determining T increases. The conducted studies have shown that the use of formula (2) reduces the error of determining the scale several times. This makes it possible to determine the values of t_n at least twice as accurately as in the methods previously used in pulsoximetry. Considering the peculiarities of recording the absorption signal using CCD, we propose to determine the position of points t_1, t_2, t_3, t_4, t_5 on the time scale by separating the processes of formation and decay of pulse wave fronts. The position on the timeline of points with t_2 and t_4 will be determined as follows. Consider the definition of time t_2 according to the waveform in Fig. 3. The moment of the end of the step formation (register charge) is determined – this is the time t_5. At time t_6, the formation of a step ends, which corresponds to the front of the pulse wave decline. In this case, the time value t_2 is located between τ_5 and τ_6.

Since the formation did not begin with the increase of another step, but there was a decrease in amplitude ΔA_5 (Fig. 3), which is smaller in amplitude ΔA_4, it can be argued that t_2 is located in the interval between t_5 and t_6 - $(t_6 - t_4)/2$. In this case, the value $t_2 = \tau_5 + (\tau_6 - \tau_4)/4$ is selected. The error in determining t_2 in this case is at least two times less than when using photodiodes to register the absorption signal. Similarly, using a comparison of the amplitudes of the ΔA_n steps, the value of t_4 is determined.

The position of points t_3 and t_5 will be determined as follows. Let us take this as an example of determining the value of t_3. The moment of the end of the step formation (register charge) is also determined: this is the time t_{n-k}. At the moment of time t_{n-k+1}, the formation of a step ends, which corresponds to the front of the pulse wave rise. In this case, the time value t3 is located between t_{n-k} and t_{n-k+1}.

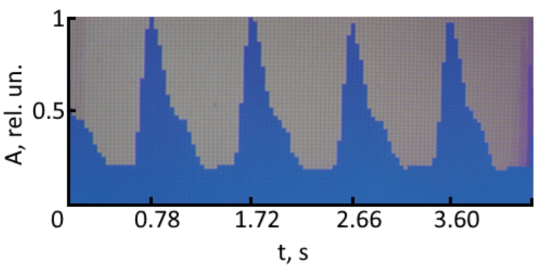

Fig. 3. Shape of the absorption signal recorded by the CCD matrix in transmission pulse oximetry
Data given for male patient (age 50)

Since the formation of another step did not begin with a decrease in amplitude, but there was an increase in the amplitude of ΔA_{n-k+1} (Fig. 3), which is smaller in amplitude of ΔA_{n-k}, it can be argued that t_3 is located in the interval between t_{n-k+1} and τ_{n-k+1} $(\tau_{n-k+1} - \tau_{n-k})/2$. In this case, the value $t_3 = \tau_{n-k} + (\tau_{n-k+1} - \tau_{n-k})/4$ is selected. The error in determining t_3 in this case is at least two times less than when using photodiodes to register the absorption signal. Similarly, using a comparison of the amplitudes of the ΔA_n steps, the value of t_5 and t_1 is determined.

Results of human health studies and their discussion

Figs. 3 and 4, for example, show registered pulse wave signals from people with various health conditions.

Visual analysis of the pulse waves presented in Fig. 3 and 4 makes it possible to notice minor deviations in their wave forms, which are quite difficult to associate with diseases. Therefore, we performed using the developed methods and ratios (1) and (2) measurements of the times t_1, t_2, t_3, t_4, t_5 by the values of which the time intervals Δt_1, Δt_2, Δt_3 and Δt_4 were determined.

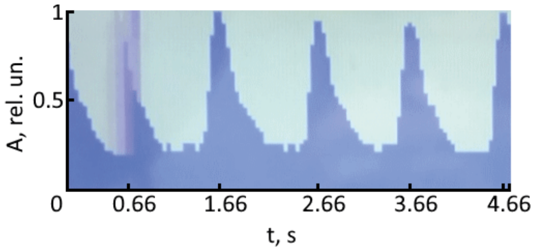

Fig. 4. Shape of the absorption signal recorded by the CCD matrix in transmission pulse oximetry
Data given for male patient (age 55)

Analysis of the data obtained shows that at higher values of the human pulse, the rate of formation of the pulse wave front is higher (the value of Δt_1 decreases) than at a low pulse. An increase in the percentage of hemoglobin oxygen saturation in the blood during the examination of 20 people showed an increase in the value of Δt_3. At the same time, in almost all of these people, the value of Δt_2 differs slightly from the values of Δt_1 and Δt_4.With a decrease in the percentage of oxygen in the blood, this difference increases. Comparisons of information about the health status of people whose pulse waves were measured and Δt determined show the possibilities of obtaining additional information for express diagnostics.

Prerequisites for further studies using the developed techniques will be an array of data from various patients for statistical processing [18–25]. In most cases, information about the disease of the cardiovascular system in these patients has been established using other methods used in clinical medicine. This will allow a more correct comparison of research results and establish new relationships between the parameters of the pulse wave to identify a number of changes in the state of the body at an early stage.

Conclusion

The obtained research results show the expediency of using the techniques developed by us for processing pulse wave fronts to obtain additional information about the work of the human cardiovascular system.

The use of the proposed methodology allows us to reduce the error by at least two times compared to previously performed measurements in determining the time intervals of Δt, which allows them to be used to determine the compliance of the arterial system.

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